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Issues concerning the evaluation of effective surface roughness of heterogeneous terrain.

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D.J. Carson

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Meteorological Office (Met. O. 20)
London Road
Bracknell
Berkshire RG12 2SZ

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ISSUES CONCERNING THE EVALUATION OF EFFECTIVE SURFACE ROUGHNESS OF HETEROGENEOUS TERRAIN

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D J Carson

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Met O 20 (Dynamical Climatology Branch)
Meteorological Office
London Road
Bracknell
Berkshire, U.K. RG12 2SZ

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D. J. Carson

Meteorological Office, Bracknell, Berkshire, England

ABSTRACT

The concept of effective areal surface roughness length is defined and three specific practical aspects of the parametrization of surface shearing stress over a heterogeneous area are discussed briefly. These are: (1) the relation of surface roughness length to terrain type; (2) the problems of areal averaging of drag coefficients and roughness lengths; (3) the parametrization of orographic influences. In particular, current conflicting views on whether surface or geostrophic drag coefficients should be averaged to give the areal surface stress are examined. The emphasis is on available practical guidance for parametrizations in numerical weather forecasting and atmospheric general circulation models.

Keywords: Roughness Length, Surface Drag, Heterogeneous Terrain, Orographic Drag, Physical Parametrization, Climate Modelling.

1. INTRODUCTION

The aim of this note is to focus some attention on an important aspect of air-surface interaction, namely the surface turbulent exchange of momentum, which has tended to be forgotten somewhat in the recent upsurge and concentration of effort to improve the understanding of the surface energy and hydrological processes, and their representation in numerical atmospheric circulation models. The evaluation of the surface turbulent momentum flux (or shearing stress) in heterogeneous terrain is an important and extremely difficult problem in its own right, and its parametrization in numerical models - whether they be meso-scale regional models or global climate models - poses a variety of as yet unsatisfactorily resolved practical problems. Three aspects of the overall problem have been selected here for brief comment.

Although only the surface shearing stress is considered, it should be borne in mind that, in most of the current generation of atmospheric general circulation models used for climate studies, the land-surface roughness characteristic (and indeed the surface stress itself) has direct and indirect effects on the turbulent exchanges of heat and moisture at the surface.

2. SPECIFICATION OF THE PROBLEM

The problem is defined in simple terms and from the numerical modeller's point of view. For simplicity, the formulae used and the subsequent discussion will assume a neutrally stable atmospheric boundary layer. The inclusion of non-neutral buoyancy effects would be an unnecessary and unwarranted additional complication which would contribute little to the discussion at this stage. For further algebraic simplicity, the vectorial character of the surface shearing stress and all winds will be ignored; only scalar magnitudes of these vectors will be used in the formulae illustrated here. The aim, in modelling terms, is to evaluate through parametrization of sub-grid scale processes the average shearing stress over an area of heterogeneous terrain defined by the model's grid size. In a global climate model the grid-element area would be typically 200 x 200 km^2 or more. In a regional meso-scale model it might be as low as 10 x 10 km^2.

The most common practice (Ref. 1) is to relate the magnitude of the shearing stress, τ, to an appropriate modelled wind speed through a simple bulk-aerodynamic formula. In local terms this might be expressed as

$$\frac{\tau}{\rho} = C_D u^2 = C_G G^2 = u_*^2 \qquad (1)$$

where, for a wind u at height z in the surface layer of the atmospheric boundary layer, it is usual to adopt the established logarithmic wind profile

$$u = \frac{u_*}{k} \ln\left(\frac{z}{z_o}\right) \qquad (2)$$

where u_* is the surface friction velocity defined by Eq. 1, k is the von Kármán constant and z_o is the local surface roughness length. Eqs. 1 and 2 define the surface layer drag coefficient C_D as a function of height and z_o,

$$C_D = \frac{k^2}{[\ln(z/z_o)]^2} \qquad (3)$$

The alternative, similar bulk-aerodynamic representation of τ/ρ in Eq. 1 (where ρ is atmospheric density, assumed constant throughout this analysis) is in terms of the surface geostrophic wind-speed, G, and the corresponding geostrophic drag coefficient, C_G. This representation of τ is dimensionally

correct and, mathematically speaking, defines C_G. It is however only of practical value in determining τ if C_G can be specified. C_G can in fact be linked to z_o (although the relationship cannot be expressed as simply as that for C_D in Eq. 3) through the so-called Rossby Number (or asymptotic) similarity theory. Buoyancy effects can also be readily included in both the surface-layer (Monin-Obukhov) and the Rossby Number similarity theories. These well known, simple relationships have been spelt out in order to emphasise, even in the simplest formulation, the highly non-linear relationship between z_o and τ.

In a similar vein, for a finite heterogeneous surface area as represented by a grid-element in a numerical model, the effective areal surface roughness length z_{oe} is related to the grid-area averaged shearing stress, $\overline{\tau}$, and the modelled grid-point winds (u_e and G_e, say) such that

$$\overline{\tau}/\rho = C_{De}u_e^2 = C_{Ge}G_e^2 = u_{*e}^2 \equiv \overline{u_*^2} \qquad (4)$$

where

$$u_e = \frac{u_{*e}}{k}\ln\left(\frac{z}{z_{oe}}\right) \qquad (5)$$

and

$$C_{De} = \frac{k^2}{\left[\ln\left(z/z_{oe}\right)\right]^2} \qquad (6)$$

Eqs. 4-6 define the effective areal parameters u_{*e}, z_{oe}, C_{De} and C_{Ge} in a manner consistent with the corresponding local expressions, Eqs. 1-3. Note that u_e and G_e are not in general the grid-area averaged values of the local u and G, but the effective model grid-point values compatible with the actual areally-averaged surface stress, $\overline{\tau}$, and the concept of the effective surface roughness length, z_{oe}, as introduced through Eq. 5.

z_{oe} is usually preferred to C_{De} (or C_{Ge}) as the basic parameter to be specified for each grid-element because it is generally expected to be an invariant which characterises the aerodynamic roughness of the surface. In contrast, the drag coefficients are known to depend on other properties such as height above the surface and stability. Obvious questions are, is it sensible to expect to be able to represent $\overline{\tau}$ so simply and, if so, how can the appropriate grid-area parameters be evaluated?

3. PRACTICAL ISSUES TO BE ADDRESSED

Attention is drawn to three specific aspects of the overall problem, each of which will be discussed briefly in this note.

3.1 The relation of z_o to terrain type

z_o (and hence the drag coefficients) is rarely estimated directly from wind profile and/or surface stress measurements and certainly for heterogeneous terrain would need to be related empirically to a qualitative description of the terrain type.

3.2 Areal averaging problems

How can z_{oe} be determined in practice for a heterogeneous area in excess of say 1 x 1 km^2? Quite clearly, from Eqs. 1-6, the local surface roughnesses cannot be averaged in any simple manner. The debate centres on the question, 'Which is the most appropriate drag coefficient to average (linearly) across the area?' Should it be the local C_D at some level within the surface layer or the local geostrophic drag coefficient, C_G ?

3.3 The parametrization of orographic influences

Comparatively little is known about the effective drag in hilly and mountainous terrains which present particularly difficult parametrization problems in models ranging from regional meso-scale models to fully global climate models with their corresponding ranges of horizontal and vertical resolutions. Practical approaches to the parametrization of orographic drag will be commented on separately from the question of areal averaging alluded to under 3.2.

The following comments on issues 3.1-3.3 stem mainly from a study of recent papers by Smith and Carson (Ref. 2), van Dop (Ref. 3), Wieringa (Ref. 4) and Mason (Ref. 5), and from discussions with all of these authors. The reader is urged to refer to the original papers for much fuller discussions of the issues.

4. THE RELATION OF z_o TO TERRAIN TYPE

The relation of z_o to terrain type, even in the absence of significant orographic effects, is an important practical issue that probably requires further attention. It is this aspect of the overall problem which is probably most relevant to the present Conference. The effective areal z_o is a derived surface characteristic which is most likely to be determined indirectly for various areal scales from 'observations' of, for example: terrain relief (elevation, slope, etc); land use; type, and distribution of the surface roughness elements. Algorithms, however qualitative, are needed to perform this function sensibly, at least in a fairly local (1 x 1 km^2) sense. Averaging over larger areas may need to be carried out initially on the basis of techniques discussed in Sections 5 and 6, until more experience is gained.

Most standard boundary-layer text books provide a table of values of z_o as a function of terrain type described qualitatively in terms of relief and vegetative characteristics (see , for example, Table 6.2 of Ref. 6). Such relationships may well be adequate on the local scale for the smoother, quasi-homogeneous types of terrain but can be expected to be less well founded for areal averages over rough, heterogeneous terrain, typical say of a European semi-rural landscape with small hills, woods, fields, crops, hedges, towns, lakes, etc.

Wieringa (Ref. 4) has recently addressed this problem in two ways:

(a) He has defined and derived a local station z_o by way of a gustiness analysis. It is claimed that the z_o thus obtained is an area-integrated parameter which allows for the effects of both nearby and far-off obstacles, vegetation, etc. in the upwind direction within a distance of about 3 km, over a sector of 20-30° width. Analysing such gustiness-derived z_o values for many hundreds of sectors in different landscapes has enabled Wieringa to relate typical roughness values to various land-use classifications. He has found that the majority of published classifications do not cater adequately for even fairly local effective z_o's in common, heterogen-

eous terrain. He suggests that one probable reason is that many of the published results are based only on wind measurements made from short masts, situated quite deliberately (and understandably) in atypical homogeneous surroundings.

(b) He found that he could sensibly correlate the gustiness-derived z_o's with a terrain classification attributed to Davenport (Ref. 7) and he has produced a table (Table 1, Ref. 4) which links the two. Wieringa recommends the use of such a table in the absence of local, gustiness-derived z_o's and Ref. 4 contains a practical example of its application in the derivation of a map for the Netherlands of 'mesoscale roughness' averaged over squares 5×5 km^2.

5. AREAL AVERAGING PROBLEMS

This issue is appropriately illustrated by comparing the methods used by Smith and Carson (Ref. 2) and Mason (Ref. 5), respectively. Bear in mind that the aim is to determine the average surface shearing stress, $\overline{\tau}$, over a finite heterogeneous area.

5.1 Smith and Carson (Ref. 2)

Smith and Carson proposed that the local geostrophic drag coefficients should be averaged over the heterogeneous area, as opposed to simple averaging of the local z_o or a low-level (i.e. surface-layer) C_D. The main reason for this is quite simple, given that the local τ cannot be integrated directly over the area concerned and so $\overline{\tau}$ must be evaluated by an indirect method. With reference to Eqs. 1-3, it is clear that for a known wind which could be assumed constant across the area, the averaging process is much simpler (i.e. linear) in terms of the drag coefficients than it is in terms of z_o. The wind which normally is most closely effectively constant over the areas concerned is the surface geostrophic wind (determined essentially from the synoptic pressure gradient), rather than say a near-surface wind which may vary quite markedly throughout the area in response to changes in the local characteristics of the underlying surface. In this case then, averaging the shearing stress is tantamount to linear averaging of the local C_G over the area. This method presumes of course that there exists a viable method for linking the local τ to the geostrophic wind such that C_G can be specified in terms of local terrain features and the meteorological conditions. Smith and Carson invoked Rossby Number (asymptotic) similarity theory in order to link locally C_G with the surface Rossby Number ($R_o = G/fz_o$, where f is the Coriolis parameter) and boundary-layer stability. The question of the validity of this approach will be raised later under 5.2.

In Ref. 2 the following procedure was adopted to produce a map of effective geostrophic drag coefficient, $C_{Ge} \equiv \overline{C_G}$, for the 10×10 km^2 Ordnance Survey squares for Great Britain suitable, it was hoped, for use in a meso-scale forecasting model.

(a) Rossby Number similarity theory was used to relate C_G to z_o, under assumptions of neutral stability and $G = 10$ ms^{-1}.

(b) Over terrain without marked orographic effects C_G was related through z_o to a terrain classification scheme (similar to the type discussed above in Section 4), suitable for application to 1×1 km^2 squares.

(c) The scheme required that each 10×10 km^2 Ordnance Survey map for Great Britain be inspected so that each 1×1 km^2 square within the map area could be allotted a value of C_G corresponding to its topographical category, selected subjectively from a 9×9 array of tabled values. Ordnance Survey maps of scale 1:25,000 were used. The 100 individual values of C_G were then averaged linearly to provide the effective geostrophic drag coefficient, C_{Ge}, for the 10×10 km^2 area.

Special rules were adopted for hilly and mountainous terrain and these will be described briefly in Section 6. The nett result was a map of C_{Ge} (strictly only for neutral conditions and for $G = 10$ ms^{-1}) for Great Britain.

5.2 Mason (Ref. 5)

Various workers have adopted alternative averaging methods for areas of heterogeneous terrain which differ substantially from the geostrophic drag coefficient method of Smith and Carson. Many, including Wieringa (Ref. 4) and van Dop (who was essentially following Wieringa: Ref. 3), have averaged drag coefficients for levels close to the surface. In some cases the areal averaging of z_o or C_D will have been carried out without due consideration for the implications with respect to $\overline{\tau}$. Mason (Ref. 5), however, has not only challenged the geostrophic-drag approach but has suggested an alternative approach which in general will produce a markedly different value of z_{oe} for heterogeneous terrain.

Mason acknowledges that the only quantity which can strictly be averaged correctly across a heterogeneous area is the surface shearing stress itself, but this is not an option normally available to us. He points out that the local surface stress does not generally result from the whole of the atmospheric boundary layer being in equilibrium with the local z_o. Indeed, it is claimed that a horizontal length scale of about 50-100 km is needed to establish a reasonable 'equilibrium' stress in relation to the geostrophic wind, i.e. to establish a true geostrophic drag coefficient. It follows then that in most circumstances in heterogeneous terrain, that although on dimensional grounds τ can be expressed formally as $\rho C_G G^2$ (Eq. 1), there is no justification to expect C_G to be determined by the equilibrium Rossby Number similarity approach, i.e. it is not generally practically viable to relate τ to G in this local sense. This criticism, if fully valid, must lay open to doubt the practical value of Rossby Number similarity theory in a wider context. I cannot offer any serious challenge to Mason's comment on theoretical grounds - but it may be that Rossby Number similarity theory can be upheld for practical purposes based on empirical, pragmatic evidence. This point needs further consideration.

Following his denouncement of the geostrophic-drag approach to determine $\overline{\tau}$, Mason outlines an alternative method. He cites evidence to support the statement that after a change in z_o the flow is only in equilibrium with the underlying surface up to a height of order $\ell \sim \frac{Lku_*}{u}$, where L is the upstream extent of the surface type. Numerical model

studies suggest ℓ lies approximately in the range $0.005\,L$ - $0.01\,L$. Further, he suggests that a 'rough rule of thumb' would be to assume no horizontal variation of the wind at a height $\ell \sim 0.01\,L$, and to average the local stresses across the area with a drag coefficient based on this height. From Eqs. 1-3 it can be seen that this method will lead to z_{oe} such that

$$\frac{1}{[\ln(\ell/z_{oe})]^2} = \sum_i \frac{f_i}{[\ln(\ell/z_{oi})]^2} \qquad (7)$$

where, for a small number of i, z_{oi} are the local roughness lengths occupying fractional areas f_i of the heterogeneous domain. ℓ itself has to be calculated from a subjective estimate of the 'characteristic scale of variations' in the z_{oi}. However, it is important to note Mason's qualifying admission that, in reality, there is no height at which the flow is both in equilibrium with the underlying surface and also independent of horizontal position in heterogeneous terrain. ℓ should be regarded as the characteristic scale-height at which the transition from equilibrium with the local surface to independence of horizontal position occurs.

Mason has compared results from his method and the Smith and Carson approach with results from numerical simulations of flow over changing z_o carried out by Nash (Ref. 8). The simulations by Nash are of flows in a periodic domain which contains a specified fraction with z_o one hundred times greater than in the rest of the domain. The simulated $\overline{\tau}$ for the whole domain is provided explicitly by the model and from this Mason derives an effective areal z_o which he considers to be the 'correct' value against which to validate the corresponding values of z_{oe} evaluated by the two alternative methods. Full details are given in Ref. 5 but it is interesting to note here that, for his method, Mason estimates $\ell \simeq 0.01\,L$ by assuming that L is typically half the domain width. Thus in the examples cited by Mason, in which the rougher z_o is always 1.5 m (therefore the smoother part of the domain has a z_o of 0.015 m), ℓ varies from only 5 m for a domain of width 1 km to a value of 500 m for a domain width of 100 km, irrespective of the relative fractions of the domain occupied by the two z_o's.

Mason's analysis shows that, in general, his method (Eq. 7) produces values of z_{oe} much closer to the Nash-derived values than does the geostrophic-drag approach of Smith and Carson. The latter approach is significantly in error on horizontal scales up to O (10 km). Further, there is a bias in the z_{oe} towards the larger values of local z_o, which becomes more significant as the length-scale characterising the surface variations decreases, and this feature of the averaging process appears to be captured correctly in Mason's approach.

As a particular example to further illustrate the different results that can be expected from the two approaches discussed here, Mason and I made independent estimates of z_{oe} for a 10 x 10 km^2 Ordnance Survey area (O.S. SU96) in southern England. The Smith and Carson value of C_{GE} converted to a z_{oe} of 0.25 m, whereas Mason's approach gave 0.50 m. We confirmed that the difference is due almost entirely to the different averaging philosophies rather than to subjective differences in our respective choices of similarity theory coefficients, etc. In general, averaging of surface-layer C_D's (as in Eq. 7) will lead to larger values of z_{oe} than implied by averaging C_G. It is perhaps also worth noting that values of z_{oe} of several tens of centimetres, for heterogeneous terrain with no marked orographic effects, are considerably larger than used typically in current global climate models (see, for example, Ref. 1).

Although Mason's arguments against the Smith and Carson approach and the evidence in support of his own method are persuasive, it is my opinion that several points remain which require further consideration and clarification. In particular:

(a) The eventual value arrived at for z_{oe} is clearly fairly sensitive to the choice of ℓ; however this is a parameter which is not defined unambiguously nor very exactly. Indeed it is recognised that strictly there is no height at which the flow is both in local equilibrium with the surface and also independent of horizontal position in heterogeneous terrain. Can the selection of ℓ be refined?

(b) Values of ℓ, sometimes of only a few metres (albeit strictly above the characteristic zero-plane displacement height), seem unduly small for actual heterogeneous terrain.

These concerns may simply reflect the fact that, in the absence of being able to evaluate z_{oe} from direct areal estimates of τ, there is no very well founded, simple and accurate indirect method. More subtly, there is an implication that estimates of z_{oe} (as defined in Eqs. 4-6), which have been shown to depend on the averaging technique adopted, might also differ with stability within each method. Also, the parametrization of only the areally-averaged surface momentum flux has been debated here: corresponding considerations need to be given to the areally-averaged surface fluxes of sensible heat and moisture.

6. THE PARAMETRIZATION OF OROGRAPHIC INFLUENCES

The discussion in the preceding Sections 4 and 5 has been for heterogeneous terrain with no significant orographic effects. Very little is known about how to evaluate effective drag coefficients (or roughness lengths) for terrain with marked orographic variability. The problem was acknowledged by Smith and Carson (Ref. 2) who proposed a simple, highly empirical formula for estimating z_{oe} in hilly and mountainous terrain. More recently Mason (Ref. 5) has examined the observational, theoretical and numerical evidence for the quantification of orographic drag and has suggested an alternative approach to its parametrization in numerical models of the type used in weather forecasting and climate modelling studies. Brief practical comments only are included here; for fuller discussion the reader must turn to Refs. 2 and 5.

Based on work by Kutzbach (Ref. 9) and Lettau (Ref. 10), Smith and Carson proposed the following formula to estimate z_{oe} in hilly areas:

$$z_{oe} \simeq 0.2\,\frac{(\overline{\Delta h})^2}{\overline{\lambda}} \qquad (8)$$

where $\overline{\Delta h}$ is the average height range between peaks and valleys over the area, and $\overline{\lambda}$ is the average distance between peaks separated by valleys,

or between successive ridges. z_{oe} is therefore proportional to the product of a characteristic slope and valley-to-peak height of the area. This formula is basically unverified and should be applied over an area much larger than that of an individual mountain, as it attempts to represent the form drag of the whole region. Smith and Carson used Eq. 8 for hilly terrain in Great Britain and the z_{oe} so determined were converted to C_{Ge} to complete their map (see Figure 4, Ref. 2). Wieringa (Ref. 4) has adopted the Smith and Carson proposal (Eq. 8) to allow for the presence of hills in his evaluation of 'meso-scale roughness' averaged over 5 x 5 km^2 areas across the Netherlands. His particular interpretation of Eq. 8 is

$$z_{oh} = 0.2\,\frac{(dh)^2}{\Lambda} \qquad (9)$$

where dh is the largest occurring terrain elevation difference over the area, and $\Lambda \approx 5$ km was found to be appropriate for the Netherlands. Wieringa (Ref. 4) also proposes a method for evaluating the effective areal roughness length in the absence of orographic effects. This initially involves the averaging throughout the area of 10-m drag coefficients to establish z_{of} (used henceforth to denote the effective areal z_o ignoring orographic effects), although ultimately z_{of} is used in conjunction with 60-m winds to evaluate $\overline{\tau}$ over the 5 x 5 km^2 areas. Although I might wish to debate the particular details of Wieringa's method, it is clear that, like Mason, he advocates averaging C_D close to the surface and considers it inappropriate to average C_G. Wieringa's nett effective roughness length, z_{oe}, is obtained by combining the local-scale effects due to vegetation, buildings, etc. with the contribution due to meso-scale orography, where the averaging across the area appears to be carried out at $z = 10$m such that,

$$C_{D_{10}}(z_{oe}) = \frac{k^2}{[\ln(10/z_{oe})]^2} = C_{D_{10}}(z_{of}) + C_{D_{10}}(z_{oh}) \qquad (10)$$

where $C_{D_{10}}(z_{of}) = \dfrac{k^2}{[\ln(10/z_{of})]^2} = \sum_i C_{D_{10}}(z_{oi}).f_i \qquad (11)$

(z_{oi}, f_i as defined for Eq. 7), and z_{oh} is given by Eq. 9. Wieringa invokes a 'blending height' analogous to Mason's ℓ, and in practice, at least for the Netherlands, this is taken as 60m. The z_{oe} inferred from Eq. 10 are used with the 60-m wind to evaluate u_{*e} and hence $\overline{\tau}$.

Mason (Ref. 5) discusses the underlying fluid-dynamical principles in his approach to the practical determination of aerodynamic drag in flows over orography. His examination of the potential and limitations of linear theories and full bluff-body dynamics has led so far to the following empirical, practical recommendations. For the area under consideration:

(a) Allocate z_{of} based on the very small-scale surface characteristics (e.g. grass, fields, woods, rocks, etc.)

(b) Estimate A/S, θ_s, $\overline{\Delta h}$

where A is the silhouette area of the surface obstacles,
S is the total surface area,
θ_s is a representative orographic slope, and
$\overline{\Delta h}$ is the typical peak-valley height (as used by Smith and Carson).

θ_s is estimated by $\overline{\Delta h}/L_s$, where L_s is the horizontal scale over which most of the height change occurs, and it is only used to determine which of two empirical rules to follow.

(c) If $\theta_s \leq 0.2$ then adopt results from linear theory and not from bluff-body dynamics. It is recommended that z_{oe} for the area be determined from:

$$\ln\left(\frac{z_{oe}}{z_{of}}\right) = 6.25\,\ln\left[1 + 63\left(A/S\right)^2\right] \qquad (12)$$

with an upper limit such that $z_{oe} \leq 0.1\,\overline{\Delta h}$.

(d) If $\theta_s > 0.2$ the following bluff-body relationship is recommended to determine z_{oe}:

$$\left[\ln\left(\frac{\overline{\Delta h}}{2z_{oe}}\right)\right]^2 = \frac{k^2}{0.5\frac{A}{S}.C_D + C_f} \qquad (13)$$

where $$C_D \simeq \begin{cases} 0.3 & 0.2 < \theta_s \leq 1.0 \\ 0.7 & \theta_s > 1.0 \end{cases} \qquad (14)$$

and $$C_f = \frac{k^2}{\left[\ln\left(\overline{\Delta h}/2z_{of}\right)\right]^2} \qquad (15)$$

with the upper-limit criterion that $z_{oe} \leq 0.1\,\overline{\Delta h}$.

Mason states that application of the above rules, Eqs. 12-15, gives results which, in many instances, are not widely different from those of Smith and Carson using Eq. 8. However, the precise differences may be significant and the procedures advocated by Mason have a slightly firmer physical basis and a more general application. Mason also draws attention to the potentially important rôle of the zero-plane displacement height in such parametrizations for complex terrain. Better guidance is needed on how this areal characteristic of the terrain can be estimated. There is clearly a great deal more work needed in this area.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. Carson D J 1982, Current parametrizations of land-surface processes in atmospheric general circulation models, Land Surface Processes in Atmospheric General Circulation Models, Editor P S Eagleson, CUP, 67-108

2. Smith F B and Carson D J 1977, Some thoughts on the specification of the boundary layer relevant to numerical modelling, Boundary-Layer Meteorol. 12, 307-330.

3. van Dop H 1983, Terrain classification and derived meteorological parameters for interregional transport models, Atmospheric Environment 17, 1099-1105.

4. Wieringa J 1985, Roughness-dependent geographical interpolation of surface wind speed averages, Submitted to Quart. J. R. Met. Soc.

5. Mason P J 1985, On the parametrization of orographic drag, To appear in the Proceedings of the Seminar on Physical Parametrization for Numerical Models, Reading, 9-13 September 1985, ECMWF. Available as Unpublished Met. Office Report, Met O 14 TDN No 177, September 1985.

6. Panofsky H A and Dutton J A 1984, Atmospheric Turbulence, Models and methods for engineering applications, New York, John Wiley and Sons.

7. Davenport A G 1960, Rationale for determining design wind velocities, J. Am. Soc. Civ. Eng. ST-86, 39-68.

8. Nash C A 1980, Preliminary results on neutral integration with a change in surface roughness, Unpublished Met. Office Report, Met O 14 TDN No 119, April 1980.

9. Kutzbach J E 1961, Investigations of the modification of wind profiles by artificially controlled surface roughness, Annual Report 1961, Dept of Meteorology, University of Wisconsin, Madison, 37-96.

10. Lettau, H 1969, Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description, J. Appl. Met. 8, 828-832.

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